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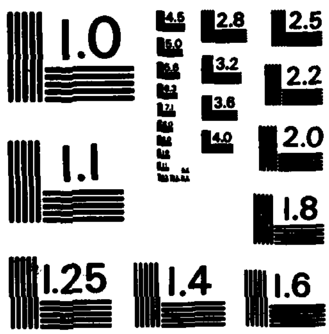

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Several results were obtained on the apparently diverse topics in the title, showing different kinds of relationships between them but with special attention to implications for new estimation algorithms and signal processing and, to a lesser extent, for system theory. The publications resulting from the work are listed by category and date. They are briefly organized and reviewed under five major headings: A) Two-Dimensional System Theory; B) Fast Algorithms for Linear Estimation; C) Adaptive Algorithms in Control Design; D) Adaptive Identification and Signal Processing; E) Stochastic System Modeling and Realization.

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SIGNAL ESTIMATION, INVERSE SCATTERING, AND
PROBLEMS IN ONE AND TWO DIMENSIONS

Thomas Kailath

F I N A L   R E P O R T

November 1, 1982

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I. Work Completed

During the period September 30, 1979, to the present, the work was largely done in cooperation with specially funded visitors at the Information Systems Laboratory. Long term visitors were Dr. Y. Genin, 1979-1980, and Dr. L. Ljung, 1980-1981, who were supported 50% by ARO. Shorter term visitors, only marginally supported by ARO funds were Drs. P. Dewilde, H. Dym, P. Van Dooren, B. Egardt, C. Samson, V. U. Reddy, B. D. Anderson and S. Y. Kung. The students who actively participated in the research during this period were B. Porat, J. M. Delosme, H. Lev-Ari, G. Panayatopulos. Fruitful and continuing developments and interactions arose from these opportunities.

Several results were obtained on the apparently diverse topics in our title, showing different kinds of relationships between them but with special attention to implications for new estimation algorithms and signal processing and, to a lesser extent, for system theory.

The publications resulting from our work are listed by category and date. We shall briefly organize and review them here under five major headings:

A. Two-Dimensional System Theory

B. Fast Algorithms for Linear Estimation

C. Adaptive Algorithms in Control Design

D. Adaptive Identification and Signal Processing

E. Stochastic System Modeling and Realization.

In reference to the list of publications, the prefix P denotes published journal papers, C denotes published conference papers, A denotes accepted papers, and R denotes papers under review.

A. Two-Dimensional System Theory

We have found that 2-D formulations often shed new light and insight on a variety of 1-D problems like:

a) model reduction for finite dimensional systems (see papers P-6, C-13, C-14),

b) analysis of nonstationary processes (see papers P-10, A-6, C-16),

c) integration of stiff differential equations (see paper P-8).

Of course, we also have some results directly denoted to the issue of

d) 2-D system theory (see papers P-7, P-13).

The work on 2-D systems was largely carried out by Dr. Y. Genin, visiting from Phillips Research Laboratories, Brussels. We are continuing to explore two aspects at the present time:

e) a search for methods of exploiting the structure present in Toeplitz-block-Toeplitz systems.

f) applications to antenna beam forming problems via algorithms for 2-D harmonic retrieval (paper R-1).

B. Fast Algorithms for Linear Estimation

There are two major classes of linear estimation problems, depending upon whether or not we have finite-dimensional (especially state-space) models for the processes involved.

a) We have obtained new results for both types of problems (see papers P-18, A-1, A-3, A-5, A-6, R-3, R-7, C-1, C-4, C-7).

b) Several invited survey papers were also written, both for engineering and mathematical audiences (papers P-5, P-9, P-14, P-19, P-20).

c) A thesis by J.-M. Delosme was completed, see attached.

d) Another thesis, by H. Lev-Ari, should be finished by December 1982.

C. Adaptive Algorithms in Control Design

Since new methods of estimation and identification lead to novel possibilities in control, research was also denoted to possible applications in control design.

The results are reported in papers P-4, R-2, R-6, R-8, C-2, C-10, C-15, C-17.

D. Adaptive Identification and Signal Processing

Our development of new estimation algorithms also led to several results in system identification and signal processing. When one is provided observations of a signal with no a-priori knowledge on either the model that generated it or on its statistical properties the problem is to obtain such information from the signal itself. Lattice filters proved to be a natural tool that combines estimation with such inference.

We have obtained several results on exact least-squares identification and estimation for the given data case. Also the applications of these algorithms to harmonic retrieval were considered. This continuing activity is illustrated by papers P-1, P-2, P-3, R-1, R-4, C-1, C-3, C-5, C-6, C-7, C-9, C-12.

A thesis by Boaz Porat made several major contributions to this area, see attached.

E. Stochastic System Modeling and Realization

Proper modeling of a stochastic process can lead to better understanding of the phenomenon and properly selected models can simplify associated estimation (filtering, prediction and smoothing) problems.

This work was begun in the previous contract period with B. D. Anderson, and continued since January 1980 with L. Ljung.

Publications in this area were P-11, P-12, P-16, P-17, A-4, R-5, C-8, C-18.

Publications Since October 1979 Under ARO Contract

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P-1 B. Porat, "The Use of Prior Information in Normalized Lattice Algorithms", *IEEE Trans. Autom. Control,* vol. AC-27, no. 4, pp. 989-990, Aug. 1982.

P-2 V. U. Reddy, B. Egardt and T. Kailath, "Least-Squares Type Algorithm for Adaptive Implementation of Pisarenko's Harmonic Retrieval Method", *IEEE Trans. ASSP,* vol. ASSP-30, no. 3, pp. 399-405, June 1982.

P-3 C. Samson, "A Unified Treatment of Fast Algorithms for Identification" *Int'l. Journal of Control,* vol. 35, no. 5, pp. 909-934, May 1982.

P-4 C. Samson, "An Adaptive L.Q. Controller for Nonminimum Phase Systems", *International J. Contr.,* vol. 35, no. 1, pp. 1-28, January 1982. .

P-5 T. Kailath, "Some Topics in Linear Estimation", *Stochastic Systems: The Mathematics of Filtering and Identification Applications, Proc. NATO Advanced Study Institute,* (Les Arcs, France, 1980), eds. M. Hazewinkel and J. C. Willems, pp. 307-350, D. Reidel, Amsterdam, 1981.

P-6 Y. Genin and S. Kung, "A Two-Variable Approach to the Model Reduction Problem with Hankel-Norm Criterion", IEEE Trans. Circuits & Systems, vol. CAS-28, no.. 9, pp. 912-924, Sept. 1981.

P-7 Ph. Delsarte, Y. Genin and Y. Kamp, "Half-Plane Minimization of Matrix-Valued Quadratic Functionals", *SIAM J. Alg. Disc. Methods,* vol. 2, pp. 192-211, 1981.

P-8 Ph. Delsarte, Y. Genin and Y. Kamp, "A Proof of the Daniel-Moore Conjectures for A-Stable Multistep Two-Dimensional Integration Formulas", *J. Philips Research,* vol. 36, pp. 77-86, 1981.

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P-11 P. Van Dooren and P. Dewilde "Minimal Cascade Factorization of Real and Complex Rational Transfer Matrices", *IEEE Trans. Circuits & Systems,* vol. CAS-28, no. 5, pp. 390-400, May 1981.

P-12 E. Deprettere and P. Dewilde, "Orthogonal Cascade Realization of Real Multiport Digital Filters", *Circuit Thy. and Applns.*, vol. 8, pp. 245-272, 1981.

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P-14 T. Kailath, Review of "Factorization Methods for Discrete Sequential Estimation" by G. Bierman, *IEEE Trans. Inform. Thy.*, vol. IT-26, no. 1, pp. 130-131, Jan. 1980.

P-15 J. S. Baras, "Noncommutative Probability Models in Quantum Communication and Multi-Agent Stochastic Control", *Ricerche di Automatica,* Special Issue on Math. Physics and System Thy., vol. 10, no. 2, pp. 217-264, Dec. 1979.

P-16 B. D. Anderson and T. Kailath, "Forwards, Backwards and Dynamically Reversible Markovian Models of Second-Order Processes", *IEEE Trans. Circuits & Syst.*, vol. CAS-26, no. 11, pp. 956-965, Nov. 1979.

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P-18 P. Dewilde and H. Dym, "Schur Recursions, Error Formulas and Convergence of Rational Estimators for Stationary Stochastic Sequences", *IEEE Trans. on Inform. Thy.*, vol. IT-27, no. 4, pp. 446-461, June 1981.

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P-20 T. Kailath, "Equations of Wiener-Hopf Type in Filtering Theory and Related Applications", *Norbert Wiener: Collected Works*, Vol. III, MIT Press, 1982.

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A-1 M. T. Hadidi, M. Morf and B. Porat, "Efficient Construction of Canonical Ladder Forms for Vector Autoregressive Processes", *IEEE Trans. Autom. Contr.*, December 1982.

A-2 T. Kailath and L. Ljung, "Strict Sense State-Space Realizations of Nonstationary Gaussian Processes", *IEEE Trans. Automatic Contr.*

A-3 T. Kailath, L. Ljung and M. Morf, "Recursive Input-Output and State-Space Solutions for Continuous-Time Linear Estimation Problems", *IEEE Trans. Autom. Contr.*, 1982.

A-4 H. Lev-Ari and T. Kailath, "Generalized Schur Parametrization of Nonstationary Second-Order Processes", *Integral Equations and Operator Theory*, 1982.

A-5 T. Kailath and L. Ljung, "Two Filter Smoothing Formulas by Diagonalization of the Hamiltonian Equations", *Int. J. Contr.*, 1982.

A-6 H. Lev-Ari and T. Kailath, "Lattice Filter Parametrization and Modeling of Nonstationary Processes", *IEEE Trans. Inform. Thy.*

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R-1 V. U. Reddy, T. Kailath and T. K. Citron, "Adaptive Algorithms for Two-Dimensional Harmonic Retrieval", submitted to *Asilomar Conference, 1982.*

R-2 W. H. Kwon, A. M. Bruckstein and T. Kailath, "Stabilizing State-Feedback Design via the Moving Horizon Method", submitted *21st IEEE Conference on Decision & Control*, 1982.

R-3 Y. Genin, P. Van Dooren, T. Kailath, J-M. Delosme and M. Morf, "On Σ-Lossless Transfer Functions and Related Questions", submitted *J. Lin. Alg. and Applns.*, 1981.

R-4 B. Porat and T. Kaila[illegible], "Normaliz[illegible] Lattice Algorithms for Least-Squares FIR System Identification", [illegible]tted [illegible]E *Trans. ASSP*, 1981.

R-5 T. Kailath and L. Ljung, "Strict Sense State-Space Realizations of Nonstationary Gaussian Processes", submitted *IEEE Trans. Automat. Contr.*, 1981, revised version, May 1982.

R-6 C. Samson, "Discrete Model Reference Adaptive Control of Nonminimum Phase Systems", submitted Systems & Control Letters, Feb. 1981.

R-7 B. D. Anderson, "A Physical Basis for Krein's Prediction Formula", submitted *Stochastic Processes & Their Applns.*, 1981.

R-8 A. Mazanov and B. D. Anderson, "Time Delays and Stable Ecosytem Models", submitted for publication, 1979.

R-9 A. M. Bruckstein and T. Kailath, "On Sliding Window Kalman Filtering and Scattering Theory", submitted 16th Asilomar Conf. on Circuits, Systems & Comp., Nov. 1982.

Published Conference Papers

C-1 C. Samson and V. U. Reddy, "Fixed Point Error Analysis of the Normalized Ladder Algorithm", *ICASSP-82, Paris, May 1982.*

C-2 P. Anderson and L. Ljung, "A Test Case for Adaptive Control: Car Steering", presented *IFAC Symp. on Thy. & Applns. of Digital Control,* New Delhi, India, January 1982.

C-3 T. Kailath "Real Time Statistical Signal Processing", presented *IFAC Conf. on Digital Control,* New Delhi, India, January 1982.

C-4 H. Lev-Ari and T. Kailath, "On Generalized Schur and Levinson-Szego Algorithms for Quasistationary Processes", *20th IEEE Conference on Decision & Contr.*, pp. 1077-1080, San Diego, CA, December 1981.

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C-7 T. Kailath, "Time-Variant and Time-Invariant Lattice Filters for Nonstationary Processes", *Proc. Fast Algorithms for Linear Dynamical Systems,* Aussois, France, Sept. 21-25, 1981.

C-8 H. Lev-Ari and T. Kailath, "Rational Approximation of Nonstationary Covariances", *Proc. Workshop on Approx. Thy.,* Louvain, Belgium, Aug. 19, 1981.

C-9 T. Kailath "Real Time Statistical Signal Processing", presented *Workshop on Information and Detection,* Inst. of Inform. Sciences, Academia Sinica, Taipei, Taiwan, Aug. 17, 1981.

C-10 L. Ljung and E. Trulsson "Adaptive Control Based on Explicit Criterion Minimization", *IFAC Congress '81,* Kyoto, Japan, August 1981.

C-11 L. Ljung, "On the Positive-Real Condition in Adaptive Control", *Workshop on Applications of Adaptive Systems Theories,* May 27-29, 1981, New Haven, CN.

C-12 L. Ljung, "Gaussian-Optimal On-Line Parameter Estimation", *Proc. 19th IEEE Conf. on Decision & Contr.,* pp. 681-683, Albuquerque, N.M., December 1980.

C-13 Y. Genin and S. Kung, "Rational Approximations with Hankel-Norm Criterion", *19th IEEE Conf. on Decision & Contr.,* pp. 486-487, Albuquerque, New Mexico, December 1980.

C-14 Y. Genin, "Two-Dimensional Reflection Coefficients and Hankel-Norm Approximations", *Proc. 1980 European Conf. on Circuit Thy. & Design,* vol. 1, pp. 475-483, Warsaw, Poland, Sept. 15, 1980.

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C-16 Ph. Delsarte, Y. Genin and Y. Kamp, "A New Algorithm for LU Decomposition with Applications in 2-D Digital Filtering", *IEEE Int'l. Symp. on Circuits & Systems,* pp. 210-212, Houston, TX, April 1980.

C-17 C. I. Byrnes, "On the Stabilizability of Linear Control Systems Depending on Parameters", *18th IEEE Conf. on Dec. & Contr.*, pp. 233-236, Ft. Lauderdale, FL, Dec. 1979

C-18 H. Dym, "Applications of Factorization Theory to the Inverse Spectral Problem", *Int'l. Symp. on Math. Thy. of Networks & Systems*, Delft, Holland, 1979.

C-19 M. R. Gevers and B. D. Anderson, "Identifiability of Closed-Loop Systems Using the Joint Input-Output Identification Method", Proc. IFAC Symp. on Identification, Dusseldorf, Germany, 1979.

Scientific Personnel:

Visitors: P. Dewilde (June-August 1978, August 1981, July-September 1982),

H. Dym (July-September 1982),

L. Ljung (August 1980-August 1981),

C. Samson (August 1980-August 1981),

Y. Genin (August 1979-August 1980)

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Abstracts of Completed Ph.D. Thesis

ALGORITHMS FOR FINITE SHIFT-RANK PROCESSES

Jean-Marc Delosme, Ph.D.,
Stanford University, 1982

Several modeling and computational problems in linear least-squares estimation are shown to be elegantly solved by exploiting the notion of shift-rank or displacement rank.

Ladder or lattice structures have recently become popular model structures in dynamic system identification and process modeling. Their main property is the ability to increase the order of a model in a simple manner. For example, in system identification, the model order does not have to be fixed a priori if the model is realized by a ladder structure. When modeling a process, one must choose the proper initial conditions, a problem which is avoided with models whose order increases with time. Until now the application of ladder structures has been limited to a smaller class of processes than the class encompassed by the fixed order structures. The ladder structures are extended in this work to a wider class of processes hence providing a better approximation to arbitrary non-stationary processes.

The notion of shift-rank, introduced a decade ago in the estimation field, is the key to such an extension. Indeed, processes modeled by constant-parameter traditional ladder structures or fixed order models are special finite shift-rank processes. We derive a generalization of the ladder structures for the whitening and modeling of finite shift-rank processes. The parameters of the generalized ladder structures are shown to be the partial correlations between the process and some random vectors related to the process.

The main step in the derivation of the generalized ladder structures is the analysis of some algorithms that determine the (inverse) Cholesky factor of the covariance of the process to be approximated by exploiting the finite shift-rank

property. Some new versions of these algorithms are developed which involve a minimal number of operations. In particular, a method of deriving Cholesky decomposition algorithms via a general elimination argument is presented and used to obtain multiprocessor (VLSI) implementations of the ladder filters.

One is often only interested in asymptotic results and the above methods, which provide partial solutions at every time instant, appear to perform unnecessary computations for such a purpose. A typical example is the determination of the minimum-phase factor of a spectrum from the knowledge of the spectrum Fourier coefficients. It has been recognized that the combination of a divide-and-conquer approach with the finite shift-rank property can be used to perform this calculation while avoiding the computation of superfluous quantities. However the proposed algorithms were not practical; the main quantities in the recursions were computed via procedures that are easily derived but extremely costly in terms of computations. We derive some explicit update formulas which improve the original procedures by several orders of magnitude and render the approach practically useful.

Contributions to the Theory and Applications of Lattice Filters

Boaz Porat

ABSTRACT

Recent research on lattice filters for nonstationary processes has been taking several directions. A considerable effort has been devoted to theoretical aspects - the generalized Levinson and Schur algorithms and their stochastic interpretation, the Hilbert space array theory, connections to circuit theory etc. On the other hand, there has been a lot of activity in more applied matters - fast algorithms for system identification and spectral estimation, whitening filters and their realizations, numerical and computational aspects, hardware implementations etc. A major part of this activity has been taking place in the Information Systems Laboratory at Stanford University. This dissertation contains a summary of the author's work in this area during the last two years. Topics covered in this work are both theoretical and applied. One contribution is in the development of a new type of lattice algorithm (the normalized covariance lattice algorithm) and in pointing out the relationship between this algorithm and the structure of the corresponding exact whitening filter. A second contribution is the development of a unified approach to given data lattice algorithms via multichannel multi-experiment embeddings. A third contribution is the development of an efficient solution to the problem of constructing lattice realizations for vector autoregressive processes parametrized by their characteristic matrix polynomials. Yet another contribution is the development of a new, so-called state-space generator approach, to orthogonal polynomials with respect to arbitrary moment matrices, and a specialization of this approach to orthogonal polynomials with respect to moment matrices of low displacement ranks. The dissertation also makes several contributions of a more applied nature. Lattice algorithms are applied to the solution of some problems in linear system theory - minimal partial realization of scalar and multivariable systems, system approximation and stability tests. The problem of autoregressive moving-average modeling of stationary time series is discussed in some detail and a new non-iterative method, based on lattice algorithms, is

developed. Finally, the dissertation makes a contribution to the problem of estimating time differences of arrival of signals in multiple source multiple sensor environments.